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ENGINEERING NOTE

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SUBJECT

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NAME

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Beam Signals Lab.

Purpose

Understand concepts of AM and FM modulation

Equipment

Spectrum Analyzer (SA)

Waveform Generator (WG)

Procedure

1.) Set WG to

Sine Wave

Freq = 1 MHz

Amp = 50mV_{pp}

AM modulation on

Modulation freq = 1 Hz

Modulation Depth = 50%

2) Sketch a display of the scope.

3) Set the SA to

1 MHz = Center freq

0 MHz = Span

10 sec = Sweptime

Scale = Linear.

Sketch the display on the SA

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4) Change modulation depth on WG to 100%

Sketch the display on the SA

Set mod. frequency to 2 Hz

Sketch the display on the SA

5)a) On the WG

Set mod freq to 1 kHz

Set mod depth to 25%

b) On the SA

Set span to 10 kHz

Set sweep time to auto

Set scale to log.

c) Record:

Number of sidebands

The frequency spacing of the sidebands

The amplitude of the sidebands
with respect to the carrier.d) Change the modulation depth to 50%
and repeat 5c.Change the modulation depth to 100%
and repeat 5c.

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5e.) Set the AM modulation depth to 50% on the WG

Set the modulation frequency to 100Hz

1 kHz

10 kHz

and repeat 5c. (You may have to change the frequency span on the SA as you change the modulation frequency.)

6) a) Turn the AM modulation off on the WG.

Turn on the FM modulation on the WG.

b) Set the modulation frequency to 1 kHz

Set the modulation depth to 100 Hz

1 kHz

10 kHz

Repeat 5c. (Do only the first 4 sidebands)

c) Set the modulation depth to 1 kHz

Set the modulation freq. to 100 Hz

1 kHz

10 kHz

Repeat 5c. (Do only the first 4 sidebands)

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7) Turn off FM modulation on the WG

Set the WG waveform shape to the Sinc function (under the Arb menu)

Set the frequency on the WG to 200 kHz

Sketch the waveform on the scope

What is the width of the pulse?

What is the spacing between pulses?

Connect signal to SA.

Set SA start freq to 0 Hz

Set SA stop freq to 10 MHz

Set SA scale to linear

Sketch Spectrum

Zoom in on spectral line.

What is the spacing between lines.

Set the frequency on the WG to 100 kHz

Sketch the waveform on the scope

What is the width of the pulse.

What is the spacing between pulses.

Connect signal to the SA

Sketch the spectrum.

Zoom in on a spectral line.

What is the spacing between lines.



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- 8) Turn on AM modulation on W.G.
Set AM Depth' to 10%
Set AM freq to 30 kHz.

Sketch Freq Spectrum.

- 9) Turn off AM modulation on W.G.

Set the Frequency to 200 kHz on W.G
(still use the Sinc function)

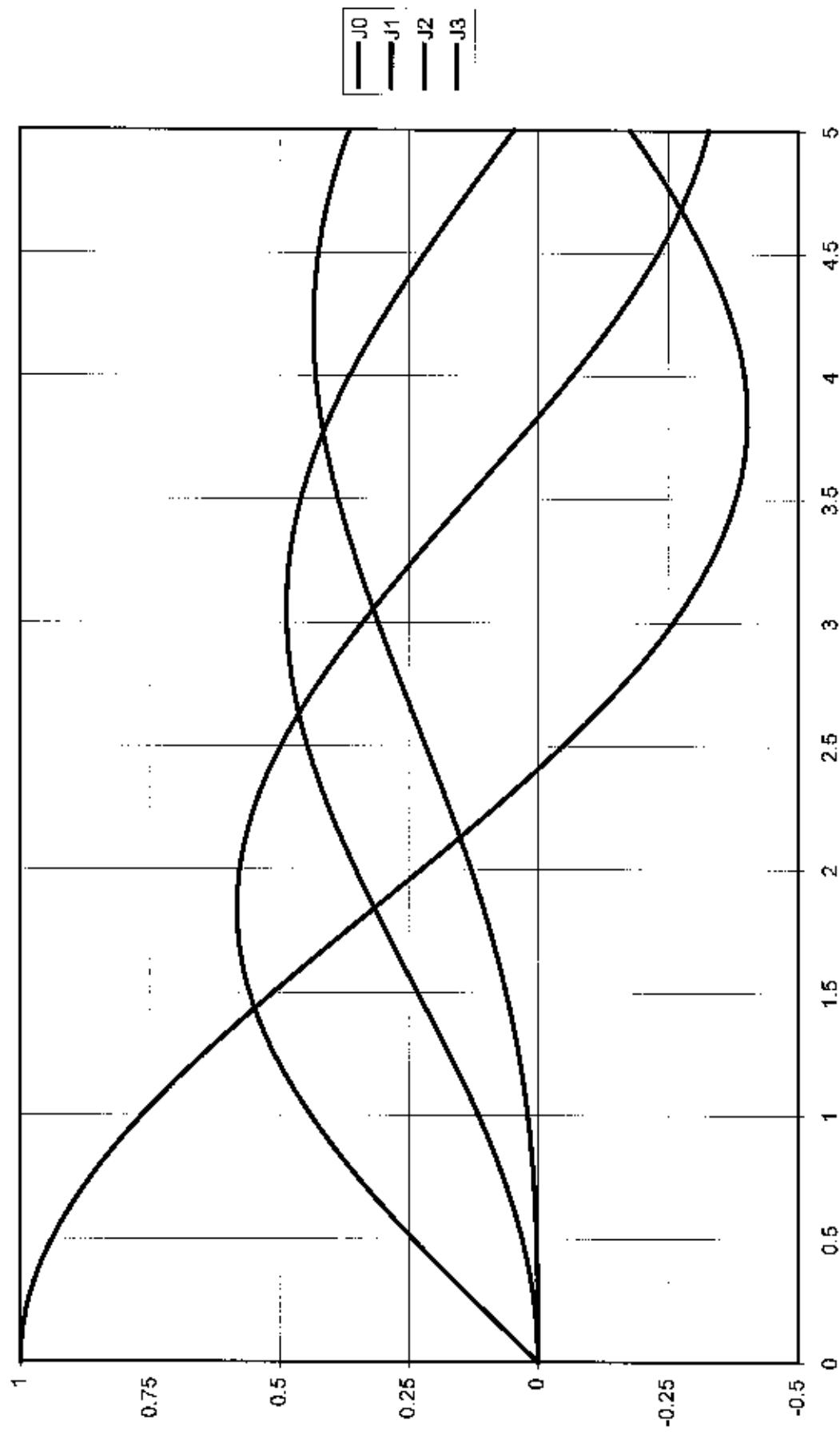
Set the Burst Count to 10.

Set the Burst Rate to 20 kHz.

Sketch Display on scope

Sketch Spectrum.

Bessel Functions



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Impedance Matching Lab.Purpose

Design, build, and test a single stub tuner matching network for matching various resistive impedances to $50\ \Omega$ at 60 MHz.

Equipment

Network Analyzer

Various mystery impedances in pumona boxes.

Assorted lengths of RG-58 cable with BNC connectors

BNC tees, bullets, and barrels

Smith Charts

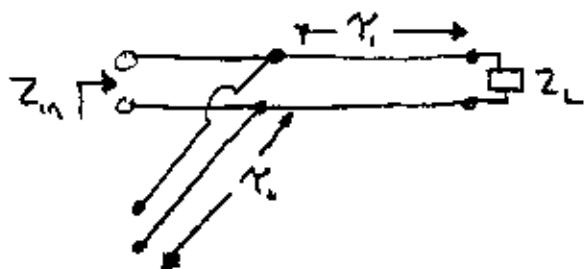
Compass & ruler

Calculator

Background Info.

A single stub tuner has the following topology.

See class notes for an example on how to design a single stub tuner.





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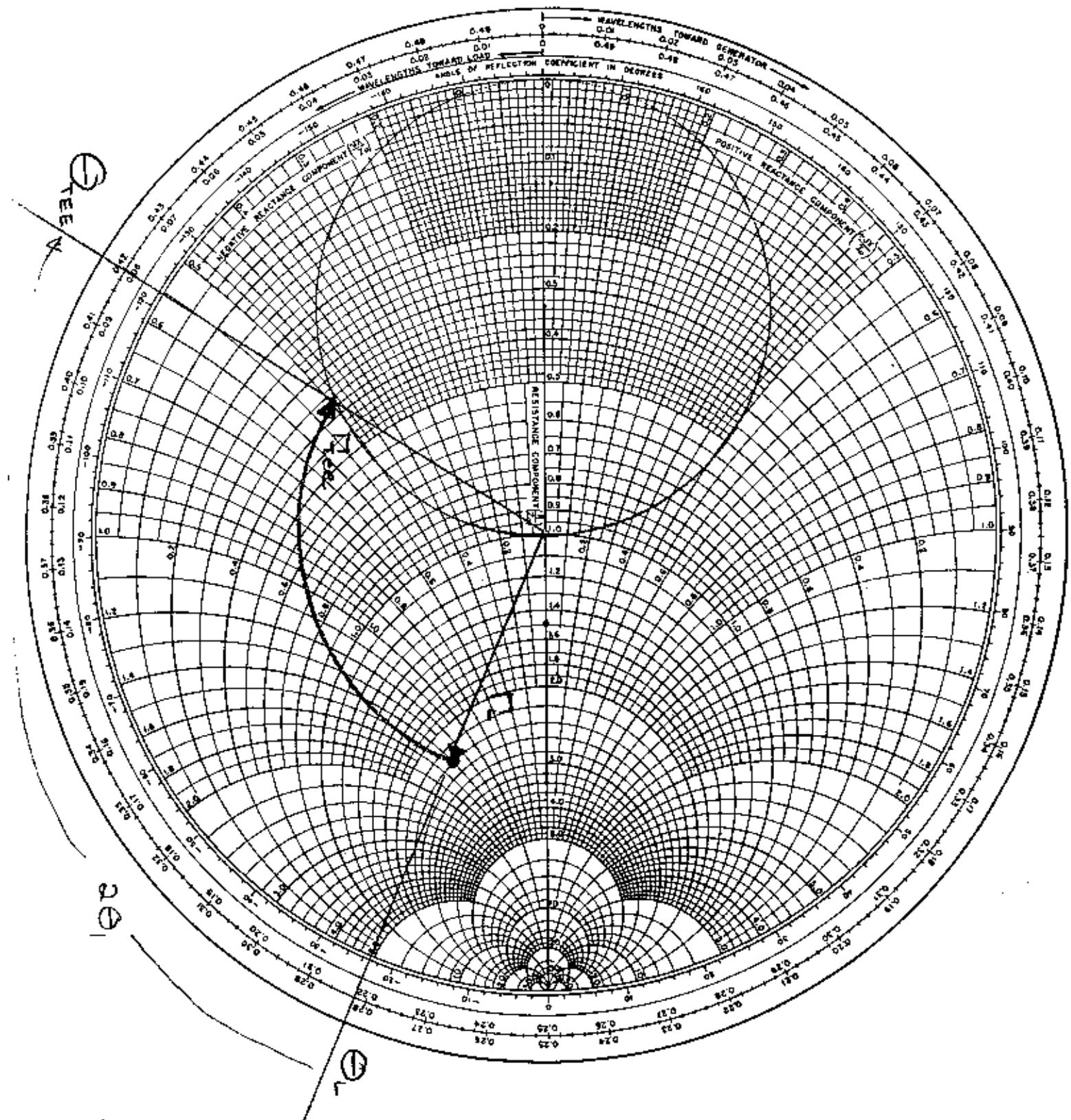
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For a given "mystery" load:

- 1) Set the network analyzer (NWA) to measure S_{11} at a center freq. of 60 MHz with a span of 0 Hz.
- 2) The cables out of NWA should be equipped with BNC adapters.
- 3) Calibrate the S_{11} measurement with an OPEN response.
- 4) Set the display format to Smith Chart and verify that the calibration is valid by measuring an "open" and a 50Ω load.
- 5) Attach a "mystery" load to port ① and measure the complex impedance and reflection coefficient.
- 6) On a Smith Chart (on paper) determine the angle needed to rotate the reflection coefficient to the "mirror" real circle.
There are 2 answers. See Smith Chart ①

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Smith Chart (1)



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7) Calculate γ_i

$$2\Theta_i = 360^\circ \cdot f \cdot 2\tau, \quad f = 60 \text{ MHz.}$$

8) Add a length of cable that is $\leq \tau_i$ to the mystery load.9) Switch the NWA display to phase format and measure the phase of the Γ of the delayed mystery load. Add BNC Bulletts and Barrels onto the load delay cable until the phase of the reflection coefficient = the phase of Γ_{TEE} 10) Measure the complex impedance and Γ of the delayed load. Does it equal Z_{TEE} & Γ_{TEE} ?



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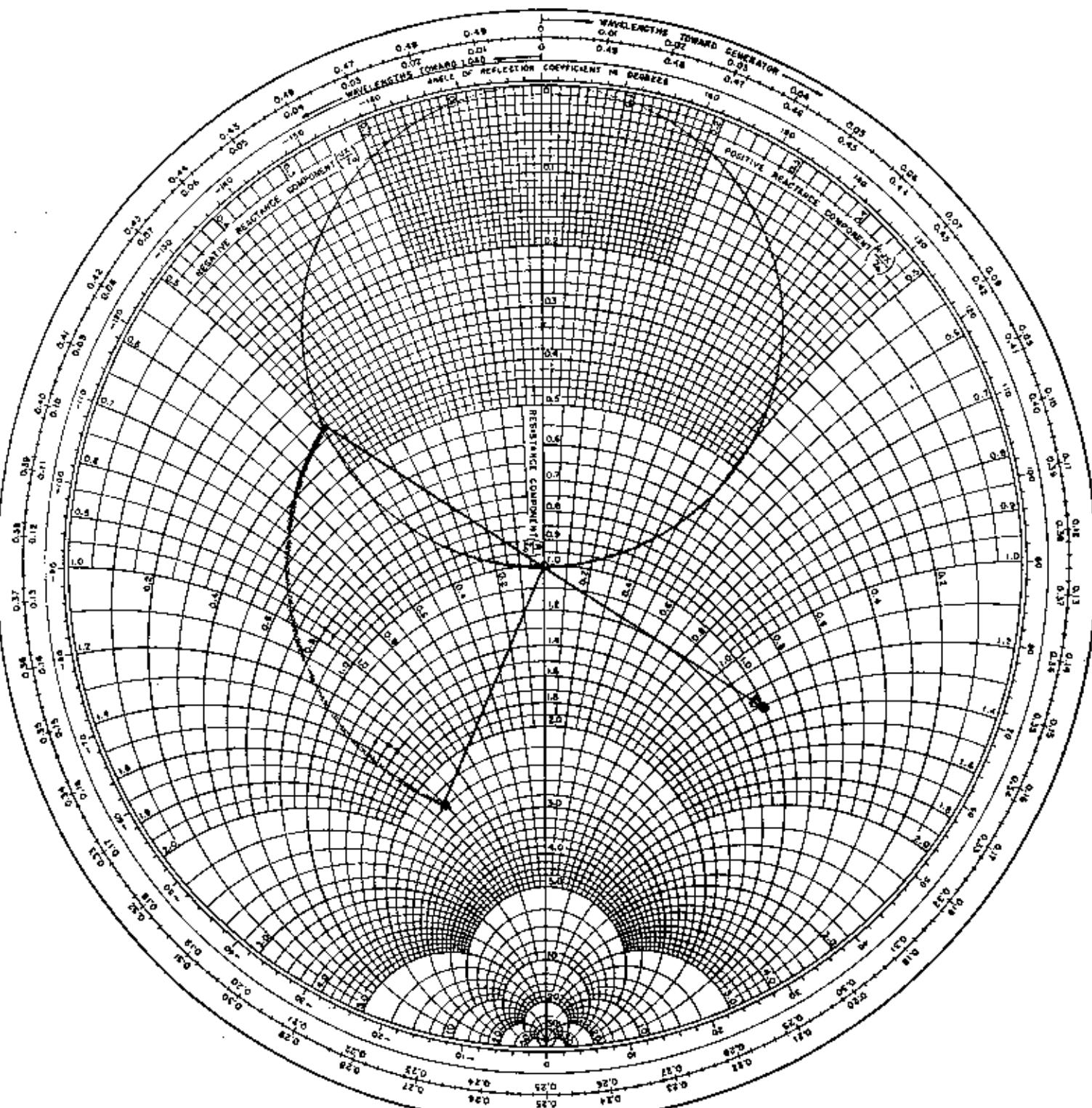
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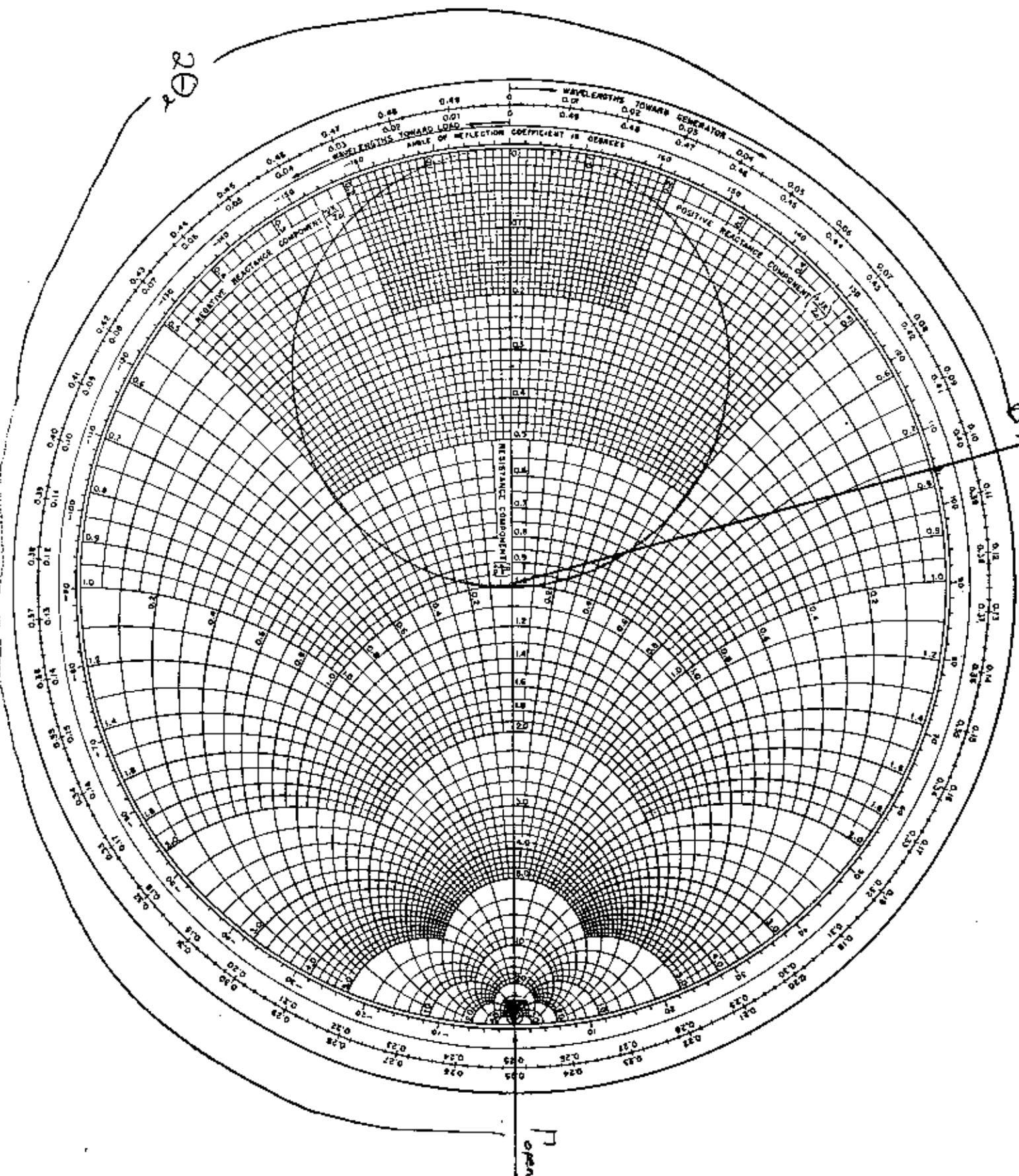
Impedance Matching Lab.

- 11). On Smith Chart, flip rotated impedance to the admittance chart and determine what value of ^{imaginary} admittance must be added to bring Π to zero. (Smith Chart 2)
- 12) On Smith Chart, determine what angle is needed to rotate the impedance of an open circuit to the value calculated in step 11. From the angle ($2\theta_a$), calculate the length of cable needed to give a phase shift @ 60 Hz of θ_2 (r_2)
(Smith Chart 3)
- 13) Remove the delayed mystery load from the NWA. Add an open circuited cable with a length $\leq r_2$ onto port ① of the NWA. With the NWA in phase format, add BNC bullets and barrels to this cable until the phase of the reflection coefficient = $2\theta_2$.

Smith Chart ②



Smith Chart (3)





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- 14) Connect the delayed mystery load and the delayed open circuit together with a BNC Tee. Measure the complex impedance and reflection coefficient. Is $Z_{\text{match}} = 50 \Omega$? Is $\Gamma_{\text{match}} = 0$?
- 15) Set the NWA to sweep from 50 to 70 MHz. Calibrate S_{11} with an OPEN response and attach the matched load. How broad band is the match. Sketch $\log |S_{11}|$ vs frequency. Sketch the frequency trajectory of S_{11} on a Smith Chart.
- 16) Try "tweaking" the match by adding or removing BNC barrels & bullets.
- 17) Repeat experiment for other mystery loads until you are sick of this lab.

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$$2\theta_1 = 119^\circ$$

$$\gamma_1 = 3.3 \text{ nS}$$

$$Y_p = -j1.08$$

$$Z_p = j.925$$

$$2\theta_2 = 336^\circ$$

$$\gamma_2 = 9.33 \text{ nS}$$

$$2\theta_1 = 240^\circ$$

$$\gamma_1 = 6.66 \text{ nS}$$

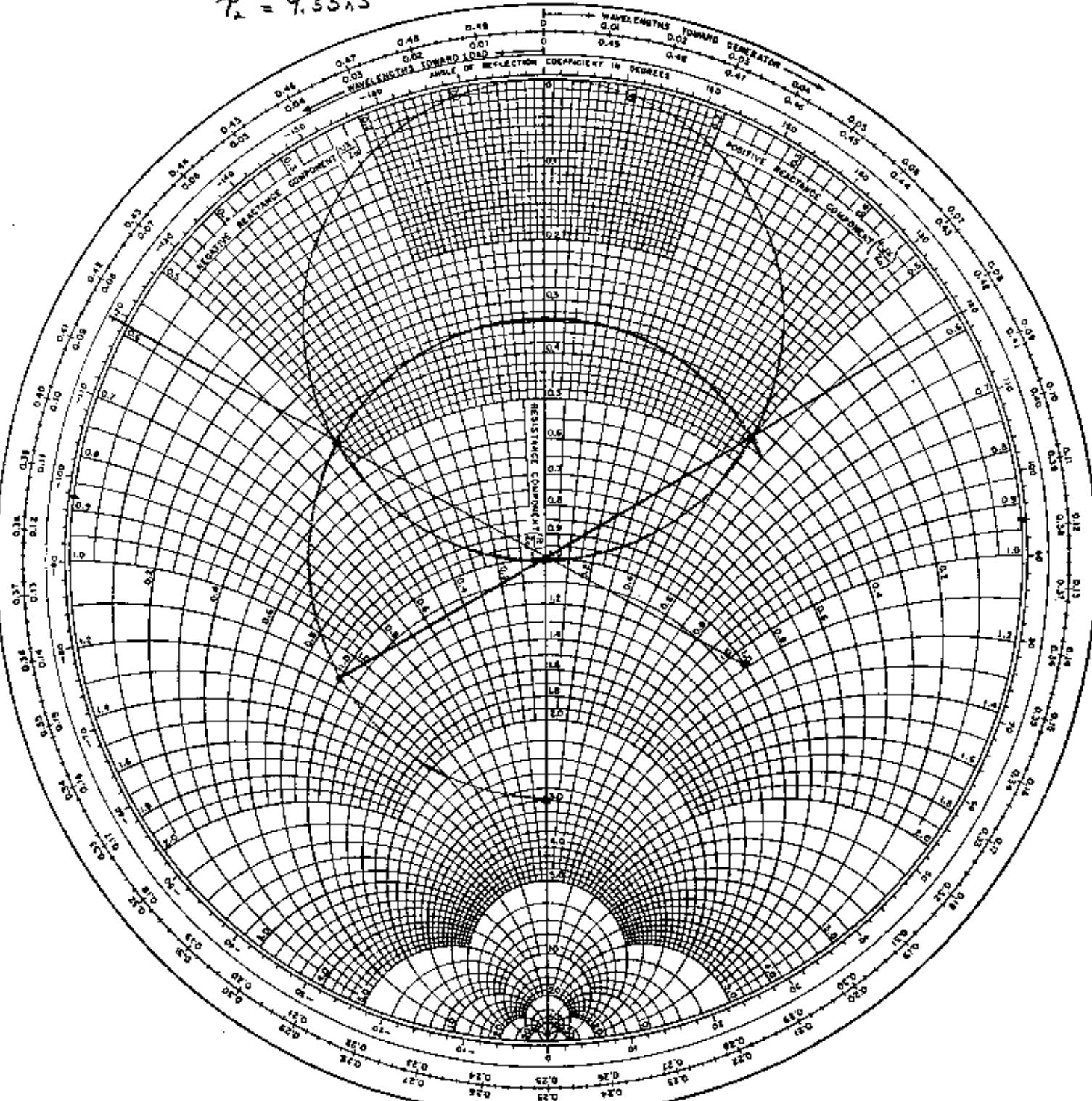
$$Y_p = -j1.15$$

$$Z_p = -j.87$$

$$2\theta_2 = 97.5^\circ$$

$$\gamma_2 = 2.7 \text{ nS}$$

150-12

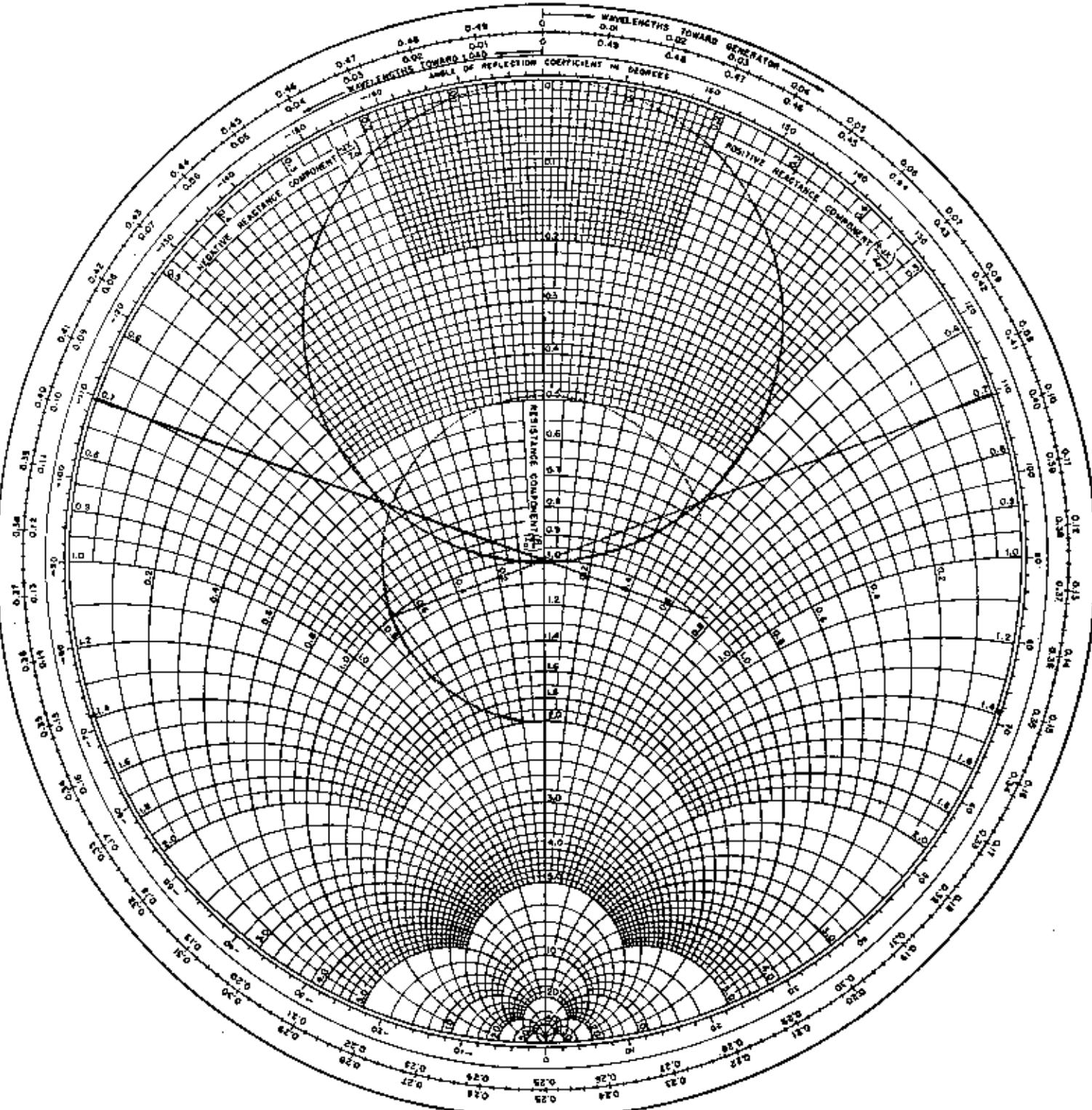


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$$\begin{aligned}2\theta_1 &= 110^\circ \\ \gamma_1 &= 3.65 \text{ nS} \\ Y_P &= -j.72 \\ Z_P &= j1.39 \\ 2\theta_2 &= 288.5^\circ \\ \gamma_2 &= 8.01 \text{ nS}\end{aligned}$$

$$\begin{aligned}2\theta_1 &= 250^\circ \\ \gamma_1 &= 6.94 \text{ nS} \\ Y_P &= j.72 \\ Z_P &= -j1.4 \\ 2\theta_2 &= 71.5^\circ \\ \gamma_2 &= 1.98 \text{ nS}\end{aligned}$$

100Ω



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RF Cavity Lab.

Purpose

- a) Measure mode spectrum of an RF cavity.
- b) Measure cavity coupling, loaded and unloaded Q of a cavity
- c) Measure electric field profile and R/Q of a cavity with a bead pull.

Equipment

Network Analyzer

3.5 calibration kit.

Single cell cavity with an E field and B field couplers.

Bead Pull Setup

Graph Paper

Calculator

Background Info

The cavities used in this experiment are aluminum mockups of the Fermilab Linac Upgrade. They resonate at about 810 MHz.

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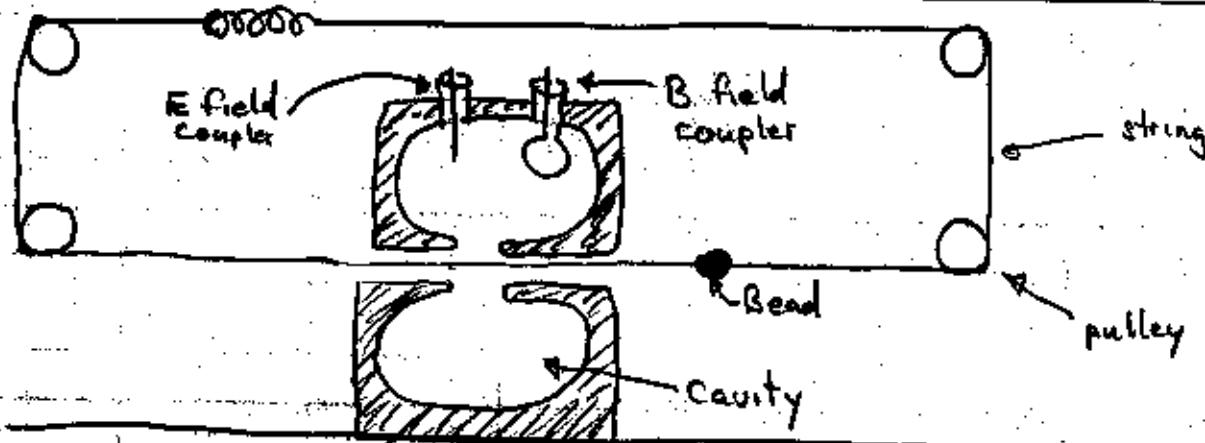
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The cavity has two couplers. One is a quasi-B field coupler in which the angle of the coupling loop with respect to the magnetic field can be changed in order to change the coupling. The other coupler is a E field coupler that is weakly coupled to the cavity.



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Procedure

- 1) Connect port ① of the NWA to the B field probe. Connect port ② to the E field probe. Reflection measurements will be done by measuring S_{11} . Transmission measurements will be done by measuring S_{21} .
- 2) In the transmission mode, find the resonant frequencies of the first 5 modes. Because the modes couple differently to the B field probe, rotate the probe 360° to make sure you can couple to all the modes.
- 3) Zoom in the NWA on the first mode. (It should be around 815 MHz). Calibrate Port ① for reflection measurements.
- 4) Adjust the B field coupling loop for a coupling of 1.
 - a) Set the display format to Smith Chart
 - b) Center the trace (it should be a circle)

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4b(cont.) around the Γ real axis as shown in the notes, by putting a phase offset into the NWA. One can also center the trace looking at the Imaginary display format and centering the trace using a phase offset.

- c) Rotate the B-field coupling loop until the coupling of 1 is achieved.
- 5) Measure the unloaded Q of the cavity by finding the frequencies in which the real part of the impedance = \pm the imaginary part of the impedance.
- 6) Knowing the coupling of the cavity, calculate the loaded Q of the cavity.
- 7) Sketch the log magnitude of the reflection coefficient vs frequency. What is the value of S_{11} at $\omega = \omega_0 \pm \frac{\omega_0}{Q_{\text{loaded}}}$ and $\omega = \omega_0 \pm \frac{\omega_0}{Q_{\text{unloaded}}}$?

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- 8) Connect Port ① to the E field probe and Port ② to the B field probe. Measure the coupling of the E field probe.
- 9) Connect Port ① to the B field probe and Port ② to the E field probe. Using S_{21} on the NWA, measure the Loaded Q of the mode. Does it agree with Step 6?
- 10) Change the B field probe coupling to 3. Be sure to re-center the cavity trace on the Smith Chart by adjusting the phase offset on the NWA.
- 11) Measure
- The coupling
 - The resonant frequency
 - The unloaded Q
 - The loaded Q with S_{11}
 - The loaded Q with S_{21}

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RF Cavity Lab.

12) Set the coupling to 1/3 with the B field probe. Repeat Step 11.

How does the resonant frequency change with coupling and why?

13) Set the coupling of the B field probe to 1 @ the fundamental mode (815 MHz). With the B field probe fixed, Repeat step 11 for the next 4 higher order cavity modes.

14) Set the NWA up for a S_{21} measurement for the fundamental mode. (The B field probe coupling should still be set at 1) With the bead outside the cavity, set the phase of S_{21} at the resonant frequency equal to zero by adjusting the phase offset of the NWA. The resonant frequency with the bead outside the cavity will be called the "unperturbed" resonant freq.



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- (5) Pull the bead slowly thru the cavity and measure the "perturbed" resonant frequency and the phase of S_{21} at the "unperturbed" resonant frequency as a function of bead position.
- (6) Repeat steps 14 & 15 for the next 4 higher order modes.

Bead Pull Analysis

The shunt impedance of the cavity is given as

$$R = \frac{1}{\sqrt{\pi}} \frac{1}{2w_0} \left[\int_{gap} \left(Q \frac{\omega_0}{w_0} (x, y, z) \right)^{1/2} dz \right]^2$$

where $\sqrt{\pi} = \pi a^3 \epsilon_0$ for a metal bead.

The electric field profile along the gap is:

$$\frac{E(x, y, z)}{V_{gap}} = \sqrt{\frac{1}{\sqrt{\pi}}} \frac{1}{2w_0 R} \sqrt{Q \frac{\omega_0}{w_0} (x, y, z)}$$

However, if the bead is very small or the electric field in the cavity is small, the shift in resonant frequency ($\Delta\omega$) might be very

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hard to measure. A more sensitive measurement would be to measure the phase shift of S_{21} at the "un-perturbed" resonant frequency as the bead is pulled thru the cavity.

The impedance of the cavity is:

$$Z = R e^{j\phi} \cos \phi$$

where

$$\tan \phi = Q \left(\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0} \right)$$

if $\omega = \omega_0 \left(1 + \frac{\Delta\omega}{\omega_0} \right)$

where $\frac{\Delta\omega}{\omega_0} \ll 1$

then

$$Q \frac{\Delta\omega}{\omega_0} \approx \frac{1}{2} \tan \phi.$$

For the measurements made in Steps 15 & 16
Calculate the R/Q of each mode and
plot $\frac{E}{V_{gap}}$ for each mode.

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McGinnis

Measuring AM modulation with a VSA

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Purpose

Use the Vector Signal Analyzer to measure properties of AM modulation.

Equipment

Vector Signal Analyzer (VSA)
Waveform Generator (WG)
Oscilloscope (Scope)

Procedure

1.) Set the WG to:

Sine Wave carrier
Carrier Freq 1 MHz
Amplitude 50mV_p
AM modulation
Modulation Freq 1 kHz
Modulation Depth 50 %
Modulation Type Sine Wave

2.) Sketch the display on the Scope

3.) Setup the VSA in spectrum mode

- a) preset the VSA
- b) Instrument Mode: Vector
- c) Center Freq 1 MHz
- d) Span 20 kHz
- e) Resolution Bandwidth Ratio: Arbitrary
- f) Ch 1 input 50Ω AC
- g) Adjust Ch 1 range

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Measuring AM modulation with a VSA

4) Sketch the display on the VSA
Explain the spectrum

5). De-modulate the signal with the VSA

- a) Set the Instrument Mode to Analog Demodulation
- b) Set the Demodulation type to AM
- c) Set the Display to 2 grids
- d) Set the Measure Data for Window A to Ch. 1 spectrum
- e) Set the Measure Data for Window B to Ch. 1 Main Time
- f) Adjust the vertical scales on both windows.
- g) Pause the measurement.
- h) Sketch the result of Window A
What are the X & Y units of the trace
What do these units mean?
- i) Sketch the result of Window B
What is the period of the waveform
What is the amplitude of the waveform

6.) Adjust Properties of AM signal on WG and repeat steps ④ - ⑤ for each of the following.

- a) AM modulation type = Square Wave
- b) AM modulation depth = 100%
modulation type = Square Wave
- c) AM modulation Freq = 2 kHz



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McGinnis

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Measuring FM modulation with a VSA

Purpose

Use the Vector Signal Analyzer to measure properties of FM modulation.

Equipment

Vector Signal Analyzer	VSA
Waveform Generator	WG
Oscilloscope	Scope

Procedure

1.) Set the WG to:

FM modulation

Carrier = 1MHz Sine Wave 50mV_r

Modulation Freq = 1kHz

Modulation Depth = 300 Hz

Modulation Type = Sine Wave

2.) Setup the USA in vector spectrum mode

a) preset the USA

b) Set the Instrument Mode = Vector

c) Center Freq = 1MHz

d) Span = 20 kHz

e) Resolution Bandwidth Ratio = Arbitrary

f) Ch. 1 Input = 50Ω AC

g) Adjust Ch. 1 range

3.) Sketch the display of the USA
Explain the Spectrum.

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Measuring FM modulation with a VSA

- 4.) De-modulate the signal with the VSA
- Set the Instrument Mode to Analog Demodulation
 - Set the Demodulation type to FM
 - Set the Display to 2 grids
 - Set the Measurement Data for Window A to Ch. 1 spectrum.
 - Set the vertical Scale for Window A to linear.
 - Autoscale Window A
 - Set the Measurement Data for Window B to Ch. 1 Main Time
 - Auto scale Window B
 - Pause the Measurement
 - Sketch the result of Window A
What are the X & Y units of the trace
What do these units mean?
 - Sketch the result of Window B.
What is the period of the Waveform?
What is the amplitude of the Waveform?
- 5.) Adjust the properties of the FM signal on the WG and repeat steps ②-④ for each of the following.
- FM modulation type = Square Wave
 - FM modulation Depth = 600 Hz
 - FM modulation Freq = 2 kHz

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Transient Measurements with the VSAPurpose

Use the Capture Mode on the Vector Signal Analyzer to examine transient frequency signals

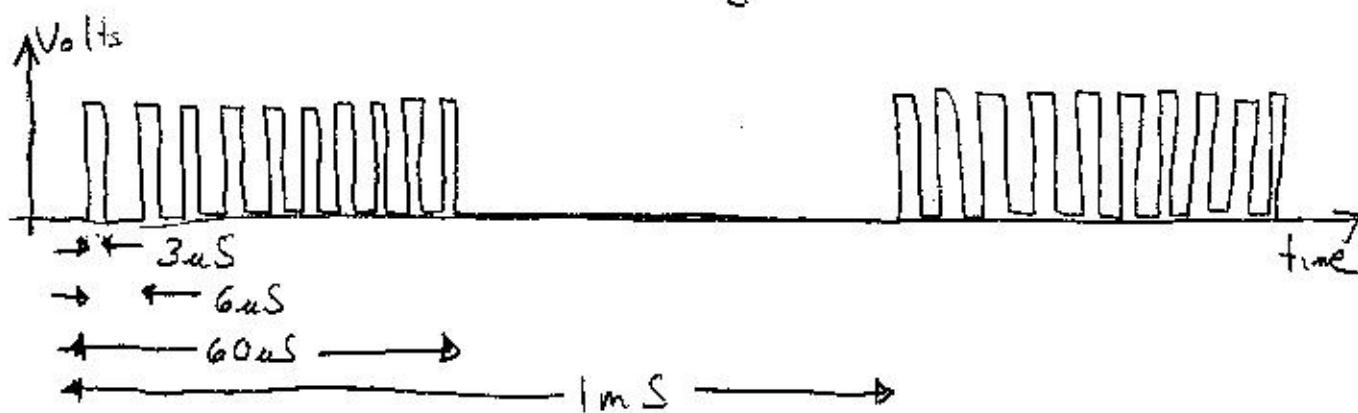
Equipment

Vector Signal Analyzer
Waveform Generator
Oscilloscope

VSA
WG
Scope

Procedure

- 1) Produce a waveform using the WG that looks like the following



10 pulses / Train

Pulse Width 3μS

Pulse Period 6μS

Train Period 1mS

Amplitude .1V



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Transient Measurements with the USA

2.) Setup the USA in Capture Mode

- a) Preset the USA
- b) Set Ch. 1 Input to 50Ω -AC
- c) Adjust the Range
- d) Set the Instrument Mode to Capture Buffer
- e) Set the Capture Buffer length to 10 mS
- f) Fill the Capture Buffer
- g) Set the Display to 2 grids
- h) Set the B window Measurement Data to Ch. 1 Spectrum
- i) Set the B window Display type to Spectograph
- j) Set the Time Overlap to 80%
What does Time Overlap mean?
- k) Press Meas. Restart & view the results
- l) Pause measurement when Spectograph "jumps"
- m) Explain the spectrum.

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USA as Network analyzer

Always use USA in vector mode

IF section.

- 1) Place ~~①~~ BNC T on USA \rightarrow Preset
- 2) Connect One end of BNC T to ch1
- 3) Set Input Z of ch1 to 1M Ω
(why?)
- 4) Connect other end of T to input of DUT (Filter) ~~correct~~
- 5) Connect output of DUT to ch 2
- 6) Set USA source type to Random Noise
- 7) Turn Source on
- 8) Adjust Range on ch1 & ch 2
- 9) ~~Set~~ Set Meas Data on ~~Window~~ Window A to ~~freq~~ response



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- (10) Turn Averaging on
- (11) Display 2 grids
Adjust B Window mess data to
freq response
& Data Format to phase
- (12) Set Res BW to Arbitrary
- (13) Set ~~the~~ x-axis format to log
for both windows
- (14) Sketch Result.

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VSA Lab.

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Purpose

Use the vector signal analyzer to look at AM & FM modulation.

Equipment

Vector Signal Analyzer (VSA)

Waveform Generator (WG)

Oscilloscope (O)

Procedure

1) Set WG to

Sine Wave

Freq 1 MHz

Amp 50 mV

AM modulation ON

Modulation Freq 1 kHz

Mod Depth 50%

Mod Type Sine Wave

2) Sketch display on Scope

3) Preset USA

Set USA ~~1 MHz~~ Inst Mode Vector

IF section

Center Freq 1 MHz

Span 20 kHz

Res BW ARB

3a) Adjust Range on Ch 1

Adjust Input to 50Ω AC

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4.) Sketch the Display on the USA

Why does it look that way?

5.) SET the USA Inst Mode to Analog Demodulation

Set the demodulation setup for Channel 1 to AM.

Sketch the result.

What is the units of the spectrum

What does it mean?

6.) Set the display to 2 grids

On ~~A~~ Screen B set the Meas. Data to Main Time Channel 1.

Pause the Measurement

Sketch the B display.

What is the period of the waveform?

What is the amplitude of the waveform?

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- 7.) Change the AM modulation type on the ~~WG~~ WG to Square Wave
Repeat Steps 2-6
- 8.) Change the AM modulation depth to 100% on the WG. Keep the square wave modulation repeat Steps 2-6
- 9.) Change the modulation frequency
Repeat Steps 2-6.
- 10.) Set the WG to
FM modulation
Carrier 1MHz
Mod. Depth 300Hz
Mod. Freq 1 kHz
Sine Wave Modulation.
- 11.) Preset USA
Set USA to Inst. Node Vector
IF Section
Center Freq 1MHz
Span 20kHz
Res BW AKB
Adjust Range
Adjust Input to 500 AC

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- 12) Sketch Display on USA
- 13) Set the USA Inst Mode to Analog Demod
Set Modulation to FM
Set the Y Scale to linear
Auto scale the display
Sketch the Results
What is the X & Y units of Spectrum mean?
- 14.) Set the display to 2 grids.
On Screen B set Mess Data
to Main Time Ch 1
Pause the Measurement
Sketch the B display
What is the period of the waveform?
What is the Amplitude of the waveform?
- 15). Re-do steps 11-14 for different Mod. Depth, Mod Freq., Mod waveforms

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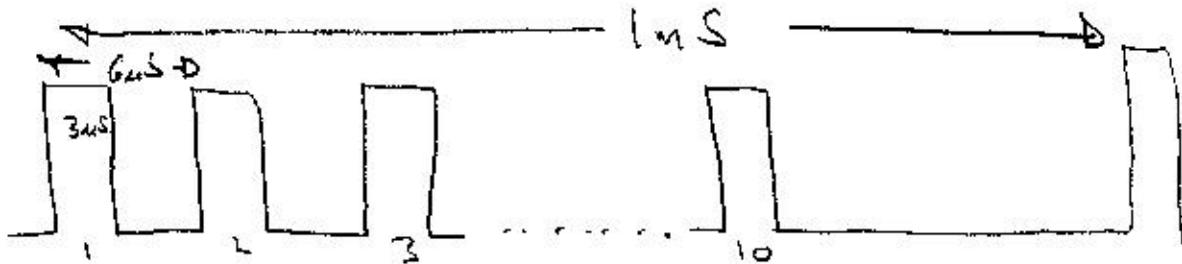
NAME

DATE

REVISION DATE

- (6.) On WG Set to Pulse Wave form
Set Pulse Period 300 μ s
Set the Pulse Width to ~~300~~ 3 μ s

17. Set the WG to the following
Wave form



10 pulses

Pulse width 3 μ s

Pulse period 6 μ s

Burst period 1mS

Amplitude ~~0.1~~ .1 V

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18) Preset the USA

Adjust Range

~~USE~~ USE IF section - Vector

Set Inst Mode to Capt Bufferer

Set Buffer length to 10 ms

Fill Buffer

Display 2 Grids

Set B window Meas Data to
Ch1 spectrum

Set B window Display type to spectrograph

Set Time Overlap to 80%

Hit Meas Restart & view results

Set Time Overlap to 20%

Hit Meas Restart to view results

Pause when spectrograph Jumps

